# Remarkable increase in tree density and fuelwood production in the croplands of northern Nigeria

Article (Accepted Version)

# Remarkable increase in tree density and fuelwood production in the croplands of northern Nigeria

## Abstract

This paper examines trends in woody vegetation and tree species composition in the Sudan zone of West Africa, using the Kano region of northern Nigeria as a case study. The study compares data on tree density, fuelwood production and tree species composition from fieldwork conducted in 1981 and 2016, as well as on several dates of aerial and satellite images since the 1960s. Recent satellite-based reports of greening in arid West Africa as a response to recovery from droughts in the 1970s and 1980s, are examined to explain the observed trends. Tree densities in the goods and services hinterland of Kano city have at least doubled since the drought period, and no decline, rather a slight increase was observed during the drought decades. This contradicts reports of woody vegetation trends from the more arid and less densely populated Sahel zone, which generally observed decline during the drought years and current recovery to pre-drought levels. The remarkable increase in tree numbers in Kano region is accompanied by increasing fuelwood production as suggested by greater concentration by farmers on tree species highly valued for fuel, at the expense of other traditional species. The main driver of such trends is thought to be rapid population growth in the context of a remaining dependence on wood as fuel by both urban and rural populations in Nigeria. Climate is thought to play only a minor role in explaining the trends. These observations confirm trends in woodfuel production observed in Kano region more than three decades previously, and indicate a somewhat Boserupian response to Malthusian-type pressures on available resources. Nevertheless, a return to rainfall levels of the drought decades combined with climate change predictions of increasing temperatures in dryland Africa, may have serious consequences for rural households if energy sources are not diversified.

**Keywords:** Fuelwood; tree density; species composition; population growth; Sudan zone; Kano

## 1. Introduction

The Fifth Assessment Report (AR5) of the International Panel on Climate Change (IPCC) predicts that temperatures in dryland Africa will rise faster than the global average during the 21st century (IPCC, 2014). Predicted changes in the rainfall regime suggest up to 20% decline in the length of growing season across the arid Sudan and Sahel zones of West Africa (Thornton et al., 2006). In this region where rainfall is already highly variable on both annual and decadal timescales, peoples' livelihoods are still closely tied to biomass production. Therefore such predictions need to be considered in the context of social and economic trends. At national level, these trends cannot be divorced from government policies which, whether intended or incidental, often have repercussions at village level. The Kano Close Settled Zone of northern Nigeria (Mortimore and Wilson, 1965) surrounds Nigeria's second largest city, Kano. Kano is the largest city in savanna Africa, and has some of the highest rural population densities in the world. The number of persons per $km^2$ almost doubled from 169 in 1991 (Tiffen, 2001) to 308 in 2006 (National Population Commission, 2006). Kano city itself grew rapidly from the late 1950s, with annual growth rates rising to approximately 6% from 2% in earlier decades. The city's population grew from 0.13 million in 1952, saw a tenfold increase over the next 40 years to 1.36 million in 1991 and then more than doubled to 2.83 million over the next 15 years up to 2006. Since 47% of the population of Kano region was below 15 years of age in 2006, there is potential for further rapid growth. Indeed, by 2050 Nigeria's population is expected to be 2.5 times its current size, reaching 440 million, and to account for 10% of all births in the world (UNICEF, 2014).

In spite of Nigeria's position as the world's 6th largest oil producer, wood remains by far the most common energy source for cooking and heating, even in major cities. Nigeria's northwestern states with 37% of the national population receive only 6% of Nigeria's fossil fuel supply (Naibbi and Healey, 2013), thus urban areas experience frequent blackouts and electricity supply is rare in rural areas. Due to the unreliability or absence of electricity in Kano, and fluctuating price of kerosene, 95% of energy used for cooking is from wood (National Bureau of Statistics, 2011).

Wood fuel in Kano has traditionally been derived from trees grown and maintained by farmers in the farmed parklands surrounding the city. Rural households derive a large variety of other basic necessities and additional income from farmland trees, which provide food, fodder, medicines, fibre and building materials (Boffa, 1999; Timberlake et al., 2010). Thus the current scenario of high and still increasing population growth combined with predictions of higher temperatures and decreased rainfall, may pose a major challenge to food security in coming decades.

Many studies have examined the relationship between biomass and climate in arid West Africa over the last three decades since satellite images were available, and certain trends are now recognised. Following many reports of rapid human-induced desertification which was being reported as recently as 2007 (UNEP, 2007), satellite observations suggest a greening trend originating in the 1980s decade, and continuing to present. This greening is seen as a response to increasing rainfall after severe droughts in the 1970s and 1980s (Anyamba and Tucker, 2005; Brandt et al., (2014a, 2014b); Capecchi et al., 2008; Hiernaux et al., 2009; Mishra et al., 2015; Olsson et al., 2005; Tappan et al., 2004), rather than to human land use pressures. But how this satellite-observed greening based on the NDVI is related to ground conditions and to local household economies has not been rigorously examined. Furthermore, it is acknowledged that the NDVI's ability to represent biomass is more representative of the green herbaceous layer than the mainly non-green biomass of woody vegetation, and the short-approximately 3-decade record of satellite images is shorter than the lifespan of many trees (Gonzalez et al., 2012).

A few more recent studies have specifically examined trends in woody vegetation (Brandt et al., 2014a; Gonzalez et al., 2012; Hänke et al., 2016; Hiernaux et al., 2009) using time-series of images combining archived aerial photographs and recent high resolution satellite images. Such higher resolution datasets have enabled the estimation of tree cover and density. As with satellite-based NDVI, trends in tree cover and tree density appear to be aligned with climatic trends. Gonzalez et al. (2012), working in three Sahelian villages in Senegal and Mauritania found an overall long term decline in tree cover in the second half of the twentieth century, and Audu (2013) gives similar warnings for northern Nigeria, although no recent survey has been done there. Brandt et al. (2014a) and Hänke et al. (2016), report similar declines in Sahelian tree cover in the later twentieth century. However, while Brandt et al. (2014a) note that tree densities are still far below the levels of the 1960s, Hänke et al. (2016) and Brandt et al. (2017) observe recovery back to 1960s levels by 2006 and 2015, respectively.

Recognising that tree densities alone may not fully represent social-ecological interactions, several studies have also considered trends in tree species composition, comparing recent field inventory with past field inventory (Herrmann and Tappan, 2013) or with informant recollection (Brandt et al., 2014a; Gonzalez et al., 2012; Hänke et al., 2016; Tappan et al., 2004; Vincke et al., 2010). Overall, a decline and shift in species diversity related to increasing aridity is reported, entailing a trend to fewer, and more drought-tolerant species at the expense of those with more southerly distributions.

By far the majority of studies of biomass trends in West Africa have been in Sahelian countries, where mean annual rainfall is 75-600 mm and grazing of perennial grasses and woody shrubs is the main land use activity. Few studies are available for the moister and more densely populated Sudan zone. In a review of remotely sensed vegetation dynamics in West Africa (Karlson and Ostwald, 2016; Knauer et al., 2014), only three of over 100 studies were of Africa's most populous country, Nigeria, where over 40% of land area lies within the Sudan zone (Figure 1). Moreover, it is likely that climate-controlled biomass impacts on local economies will be country-specific due to differing government policies, particularly those relating to energy distribution and energy subsidies (Cline-Cole and Maconachie, 2016). Previous investigations of tree densities in the Kano Close Settled Zone of northern Nigeria (Mortimore and Wilson, 1965) indicated an approximate 23% increase in tree densities surrounding the city between 1972 and 1981, and slight decline in the outer hinterland (Nichol, 1989; Cline-Cole et al, 1990). However, these data were collected in the early 1980s before the full effects of the 1970s to 80s drought on tree stocks, and when population was less than half that of today. More recent reports from farm questionnaires have indicated declining tree stocks around Kano (Maconachie and Binns, 2006; Maconachie et al, 2009).

The main objective of the current study is to examine trends in woody vegetation abundance and composition in the Sudan zone of West Africa, using the farmed parklands surrounding Kano, northern Nigeria as a case study. Kano's status as the largest city in savanna Africa, with probably the highest rural population densities, provides a model for understanding social-ecological interactions under a scenario of climate change and population pressure. The study is based on historical data from archived aerial photographs and satellite images, as well as field data collected in the early 1980s and 2016.

## 2. Materials and Methods

### 2.1 Study area

The research was conducted in three study areas surrounding Kano city (Figure 1), which is situated at 12° N in the northern Sudan Zone of West Africa. Kano's mean annual rainfall of 750 mm, supports a natural vegetation of tree savanna, with flat-topped trees browsed by savanna fauna and livestock, when grass is unavailable during the October to April dry season.

Rainfall is highly variable both inter-annually and on a decadal timescale (Figure 2). Severe drought in the 1970s and 80s was experienced throughout West Africa, but rainfall in Kano appears to have recovered to 1960s levels. The Kano Close Settled Zone (Mortimore and Wilson, 1965) describes the densely populated agricultural region influenced by the proximity of Kano and serving as its hinterland in terms of interdependency of products, trade goods and services. Over 80% of the land is cultivated in the April to September rainy season, with main subsistence crops of Guinea corn, Millet and Sorghum. Vegetables are grown along valleys and on irrigation schemes. The 'parkland' landscape is defined by the large variety of trees propagated and maintained on farmland, which are used for a very wide variety of purposes including medicinal use, food, fibre, construction and as fuelwood (Boffa, 1999; Timberlake et al., 2010). Traditionally, goods were brought to Kano markets by donkey, limiting the fuelwood hinterland to around 50 km, but replacement by pickup trucks over the last two decades has expanded this to over 100 km. Questionnaires to farmers in the Kano Close Settled Zone (Maconachie et al., 2009; Maconachie and Binns, 2006; Maconachie, 2013) indicate that farmers perceive declining tree cover on farmlands, as well as reductions in tree species diversity in recent decades.

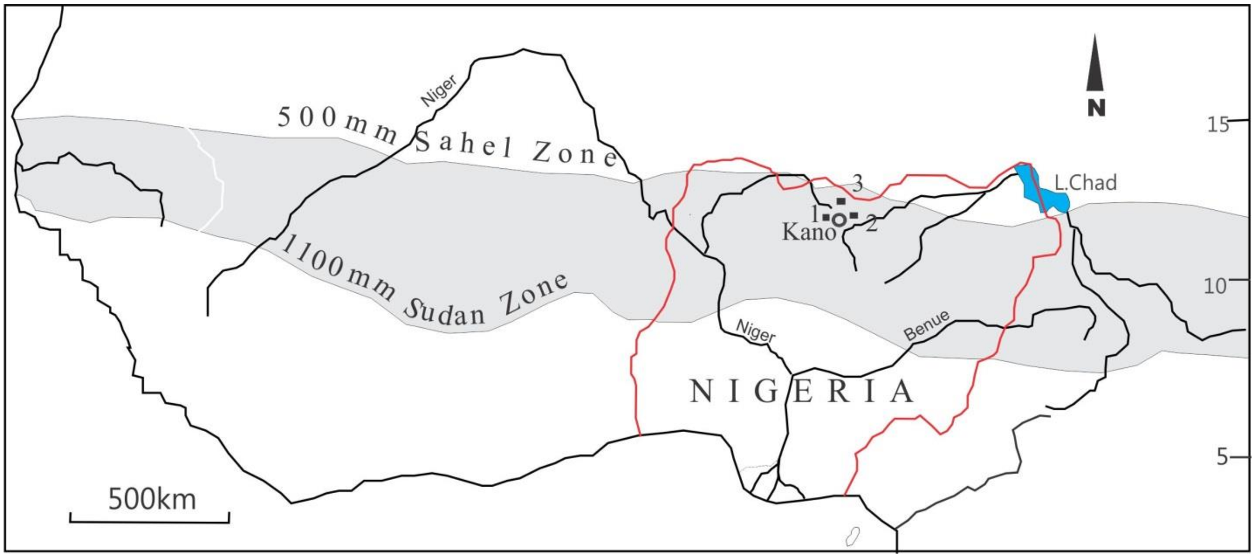



**Figure 1.** Climatological zones of West Africa showing location of study areas.

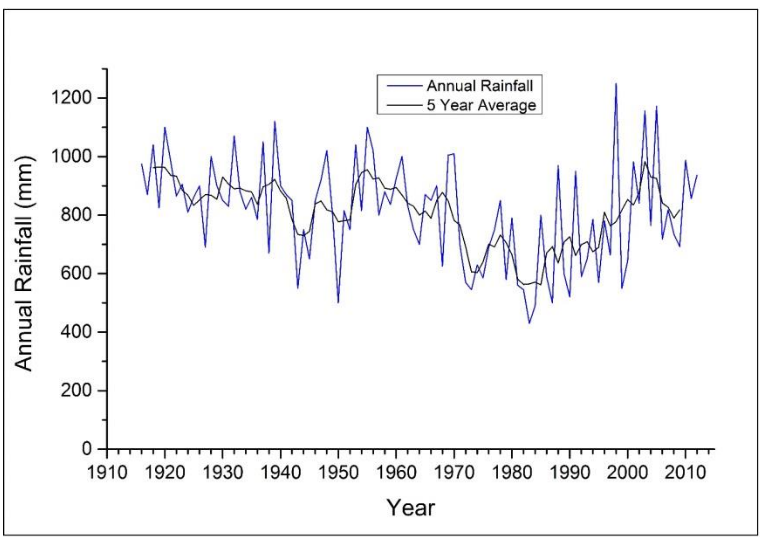



**Figure 2.** Annual rainfall amount and the five-year moving average at Kano, Northern Nigeria, 1916 to 2010. Source: International Institute for Tropical Agriculture (IITA), Kano station (Mortimore, 2000).

Three study areas (Figure 1, Table 1) were selected within Kano's hinterland as follows. Study area 1, Kano West extends westwards from Kano city covering 100 $km^2$, and Study area 2, Kano East is situated in the region of the Jakara river, 30 km northeast of Kano city and covers 110 $km^2$.

These two study areas represent the long-established Kano Close Settled Zone of intensive agriculture and high rural population within a day's walking or donkey distance to the city market. They were selected based on their geographical differences, with mainly red, well-drained sandy loam soils in Kano West, compared to Kano East dominated by the Jakara river lowlands draining into the Hadejia river and ultimately, Lake Chad. Soils in Kano East are heavier, yellow-red to grey in colour, with more clay. Study area 3, Daura, covering 200 km$^2$, was selected farther north bordering the more arid Sahel Zone, where only approximately 60-70% of land is cultivated, compared with over 90 % in Kano West and Kano East. At 100 km northward from Kano, Daura area has become a source of rural produce by pickup truck for Kano city over the last two decades. The geographical differences between the three study areas provide a range of social-ecological conditions, within which human responses to climatic and economic pressures may differ.

**Table 1**. Image datasets and field survey.

| Study areas | Location | Study area size (km$^2$) | Population density (persons/km$^2$)# | Corona satellite images | Aerial photographs | Recent satellite images | Field Survey Date | Field Survey area (ha) | No. of Plots |
|---|---|---|---|---|---|---|---|---|---|
| Study Area 1 | 11.96° N, 8.38° E, | 100 | 454 | 1967 | 1981 | 2014 (WV2) | 1981, 2015-16 | 37 | 21 |
| Study Area 2 | 12.25° N, 8.75° E | 110 | 397 | NA | 1972,1981 | 2013 (WV2) | 2015-16 | 137 | 25 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Study Area 3 | 13.0° N, 8.25° E | 200 | 232 | 1967 | 1991 | 2015 (Google Earth) | 2015-16 | 60 | 31 |

#(National Population Commission, 2006).

## 2.2 Field data collection

Fieldwork conducted in the three study areas during the 2015-16 dry season provides the basis for the study, and historical trends are observed from field data collected 34 years earlier in 1981 in Study areas 1 and 3 (Nichol, 1989). Field survey quadrats in each study area (Table 1) were selected by stratified random sampling in order to ensure a representative range of tree densities. The stratification was performed by dividing the study area into four classes of tree canopy cover based on an NDVI image derived from WV2 data. Approximately even numbers of quadrats per strata were randomly selected for all study areas according to Karlson et al. (2014). Rectangular quadrats of different size were selected according to tree density variations among study areas. Field data collected included enumeration of tree numbers for trees > 5 cm in diameter, height of trees, measurement of Diameter at Breast Height (DBH), as well as species identification. For each field surveyed quadrat, the location of every individual tree was manually located on a color print of a Worldview 2 (WV2) pan-sharpened image of 0.5 meter resolution. From this, a GIS based point shapefile of field tree locations was generated for further analysis.

For study area 1, field survey was conducted for 21 quadrats (1-2 ha in area, totaling 37 ha), and these were then located on the archived images of 1967 (Corona images), 1981 (aerial photographs) and 2014 (WV2). For study area 2, field survey was conducted for 25 quadrats (2-10 ha in area, totaling 137 ha), and these were then located on archived aerial images of 1972, 1981 and 2013 (WV2). For study area 3, field survey was conducted for 31 quadrats (2 ha in area, totaling 62 ha), and these were then located on the archived images of 1967 (Corona), 1991 and 2015.

As the very marked increase in tree densities observed in all three study areas was surprising, especially when compared with other reports of trends in woody vegetation in West Africa, we decided to extend the survey to a larger area outside the study area plots using images alone. Therefore, an additional 67 square plots each of 1 ha area, 35 plots of 4 ha and 20 plots of 4 ha were randomly selected for study areas 1, 2 and 3 respectively, and tree densities were calculated for three different time periods, by manual counting of trees on images.

To supplement and confirm observed trends in farmland trees, 40 questionnaires were administered to farmers in 20 different villages in both study areas 1 and 3. Farmers selected were over the age of 40, to allow for recollection over previous decades.

### 2.3 Image datasets

Remote sensing images were used to survey areas beyond the actual field plots, as well as for years when field data were unavailable (Table 1). Thus for Study area 1, we determined past tree densities from Corona satellite images of September 1967, aerial photos at 1:25000 scale by Kenting Africa in 1981, and recent tree density from a WV2 image of 2014 (panchromatic band at 0.5 m resolution and multispectral bands at 2 m). Pan-sharpened images at 0.5 m resolution were produced using the Hyperspherical Color Space (HCS) method (Padwick et al., 2010) by fusing multispectral bands at 2 m with the panchromatic band at 0.5 m. For Study area 2, Kano East, we had aerial photos of March 1972 at 1:40000 scale and 1981 by Kenting Africa at 1:25000 scale, and recent WV2 imagery of 2013. For Study area 3, Daura, we had Corona satellite images of September 1967, aerial photographs of 1991 at 1:25000 scale acquired by Geonex during the Katsina Arid Zone Programme, and recent high resolution IKONOS satellite images in Google

Earth of 2015. Corona images were acquired by U.S. earth observation satellites with a ground resolution of 1.8 meter (McDonald, 1995).

As raw Corona images and aerial photographs lack positional information, these were georeferenced using Google Earth images as a reference. For each aerial photograph, 20-25 control points were selected and rectification was performed with a first order affine transformation method (Hazewinkel, 2001), rounding the input cell size to 0.5 meter. As the Corona images covered a larger area, they were divided into small sections of 25 $km^2$, and individually georeferenced using 20-25 controls points with input cell sizes rounded to 2 m. For direct comparison between years, image-to-image registration was carried out to an accuracy of 2-3 meters for aerial photographs, and less than 5 meters for Corona images.

## 2.4 Recording of tree densities

Tree counting on images was validated using the field plots as the reference dataset. It was observed from this, that at least 4 pixels are required for identifying a tree using the sharp contrast between the dark tree crown and its bright soil background on dry season images. Therefore on the 0.5 m resolution of the more recent (1980s to 2015) images a small tree with crown size of 4 $m^2$ area covers 16 pixels and can be easily identified. However, as the Corona images of 1960s used in Study areas 1 to 3, and the aerial photographs of 1972 for study area 2, had lower resolution than the more recent aerial photographs and high resolution satellite images, some undercounting of smaller trees may have occurred for the pre-drought period.

For all three study areas, Corona satellite images obtained in the 1960s and aerial photographs obtained in the 1980s and 1990s respectively, provide information on tree densities before and during the 1970s to 1980s drought, whereas recent satellite images and field data indicate post-drought conditions.

## 2.5 Timber volume and fuelwood volume

Not all species are used for fuel, for a variety of reasons from poor burning properties to local folklore. Thus it is important to distinguish between timber volume which includes all species, and fuelwood volume only those species which can be used for fuel. For this reason, the tree *Adansonia digitata*, (Baobab), is not included with fuelwood volume (Table 3), as its wet and spongy wood precludes it from fuel use. The definition ‘fuelwood volume’ here could strictly be defined as ‘potential fuelwood volume’, as wood may also be used for boundary markers, fencing and furniture. However, as these are one-off uses whereas fuelwood demand is continuous, it is likely that the woody component of trees whose leaves, fruits and bark are used for medicinal, food and other purposes, would be periodically lopped and eventually felled for fuel.

Although wood volume includes canopy as well as trunk wood, since we were unable to carry out destructive sampling, volume is computed from $\pi R^2 H$ for the volume of a cylinder, based on field measurement of DBH and tree height. This also allows direct comparison with the 1981 field data.

## 2.6 Tree species composition

To evaluate tree species composition for trees recorded in fieldwork of 1981 and 2016, the Importance Value Index (IVI) was calculated (Equation 1), using data from all quadrats in a study area.

$$\text{IVI} = (\%)\ \text{Basal Area} + (\%)\ \text{Density} + (\%)\ \text{Frequency} \qquad (1) \qquad \text{(Kershaw, 1974)}$$

Histograms of DBH size spectra were constructed, by division of the total DBH values for each species into six size classes, to indicate the approximate relative age and thus the regeneration status within a study area. In many natural situations such as undisturbed woodland small trees would comprise the largest size class with an even rate of decrease to the largest class, resulting in a smooth L-shaped curve. In human disturbed situations a smooth curve is rarely seen and in farmed parkland where farmers protect trees, more large and old trees would be expected (Condit et al., 1998; Lykke, 1998).

# 3. Results

## 3.1 Tree densities

The objective of tree enumeration was to identify individual trees on time-series of images before, during and after the 1970s to 80s drought, to set recent satellite- and field-based observations of greening in context of long term climate variability. Therefore the results (Table 2) are grouped according to pre-drought, drought and post-drought periods.

In study area 1, fieldwork conducted during the 2015-16 dry season indicated 25 trees per ha, which represented a doubling in tree numbers since the previous fieldwork in this study area in 1981, when 12.3 trees/ha were recorded. Aerial photographs of 1980 (but from different plot locations within the study area) indicate 14.9/ha, which is a similar order of magnitude to the 1981 fieldwork. Tree density in the pre-drought year of 1967 appears similar to the 1970s to 80s drought period (confirmed from both 1981 fieldwork and air photos), with 12 trees/ha, but again far below the 25 trees/ha recorded in the recent 2015-16 dry season. The field survey of 2015-16 shows a 31% increase from the WV2 image of 2014, which may represent a recent upturn in the increasing trend in tree densities (Figure 3).

In study area 2, tree densities have been 50% lower than in Study area 1 for all three periods, thought to be due to the heavier clay soils which are more difficult to cultivate and may prevent natural seedling regeneration. However trends are similar in that tree numbers held constant from the 1960s up to and including the drought period, with only a 5% increase, and a doubling of tree numbers has occurred since the drought years up to the present period (Figure 4). As in Study area 1, the field survey of 2016 shows a marked increase in tree numbers (of 18%) since the WV2 image of 2013, which may represent a recent upturn in the long term increasing trend in tree densities (Figure 3).

**Table 2.** Tree Density from field survey plots and aerial photographs.

| PERIOD | PRE-DROUGHT | DROUGHT PERIOD | | POST-DROUGHT | |
|---|---|---|---|---|---|
| | 1967 | 1981 | 1981 Field survey | 2014 | 2016 Field Survey |
| Study Area 1 | 12.5 | 14.9 | 12.3 | 19 | 25 |
| Study Area 2 | 5.6 (1972) | 5.9 | NA | 11 (2013) | 13 |
| Study Area 3 | 7.8 | 10.6 (1992) | 6.5 | 20.9 (2015) | 22 |

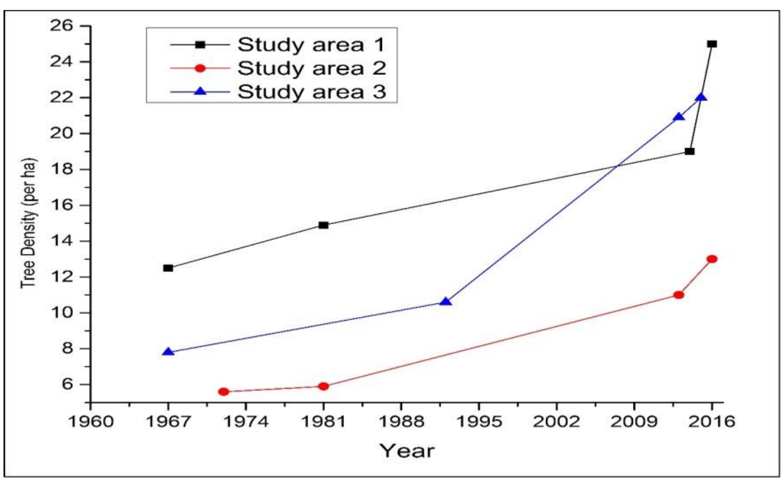



**Figure 3.** Trends in tree density for 3 study areas.

In Study area 3, the 25-year period from 1967 to 1991 saw a significant (approximately 35%) increase in tree density, and in the following 24 years from the post-drought period to present, a doubling of tree densities is observed. Thus the rate of increase observed between the 1960s up to the drought period, has itself substantially increased since the drought.

The results for the additional three extended study areas surveyed on images alone, confirmed the observations of large increases in tree numbers over the study period, with similar trends of an approximate doubling in tree densities in Study areas 1 and 2, and a threefold increase in Study area 3.

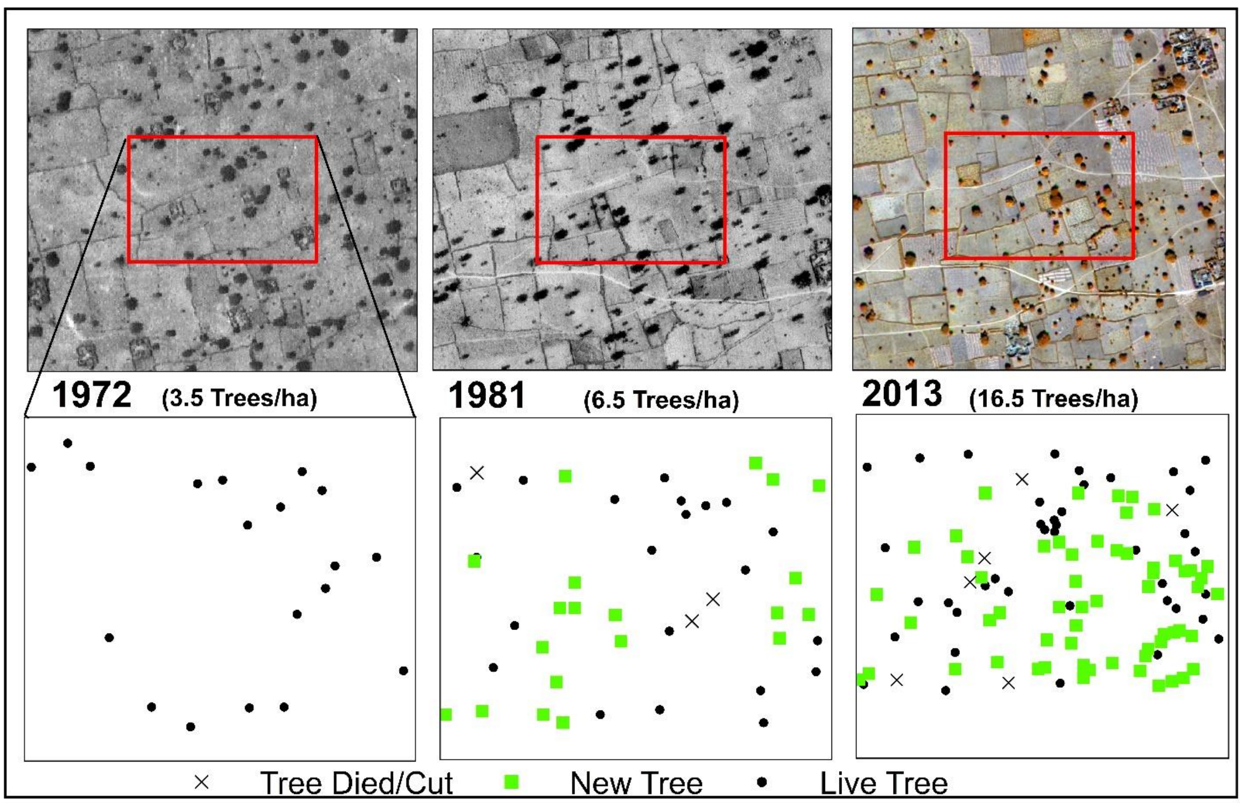



**Figure 4.** Change in tree stocks over 45-year period in Study area 2- at 1:2500 scale, and size of rectangle 3 by 2 ha.

## 3.2 Fuelwood volume

Study area 1, with the highest tree density, also has much higher fuelwood production than the other two study areas (Table 3). Study area 2, with approximately half the tree density of study area 1, has correspondingly, roughly only half the timber volume, but 62% of the fuelwood volume, which may suggest the importance of wood fuel among tree products in the local economy even in an area with fewer trees. In study area 3, with similar tree densities to study area 1, both timber volume and fuelwood volume are significantly less (64% and 67% respectively) than in Study area 1, due to the smaller size of trees in this northerly study area bordering the Sahel zone. In terms of trends it is remarkable that fuelwood production has tripled since 1981 in Study area 1 and increased by 6 times in Study area 3. In 1981 study area 3 was not within the fuelwood hinterland of Kano which was then defined by donkey distance per day, but has now expanded to over 100 km with pickup trucks. Discussions with farmers indicated that they rarely purchase wood, suggesting a plentiful on-farm supply.

**Table 3**. Timber volume and Fuelwood volume (cubic meter per hectare) from fieldwork in 1981 (in brackets) and 2016.

| | Timber volume | Fuelwood volume |
|---|---|---|
| Study Area 1: 2016 (1981) | 40.3 (12) | 27 (8.9) |
| Study Area 2: 2016 | 20 | 16.8 |
| Study Area 3: 2016 (1981) | 25.7 (54)* | 18.2 (3.3) |

* The field data reported for Study area 3 in 1981 were collected from a different location, north of Kano but at the same latitude as Study area 3.

## 3.3 Species trends

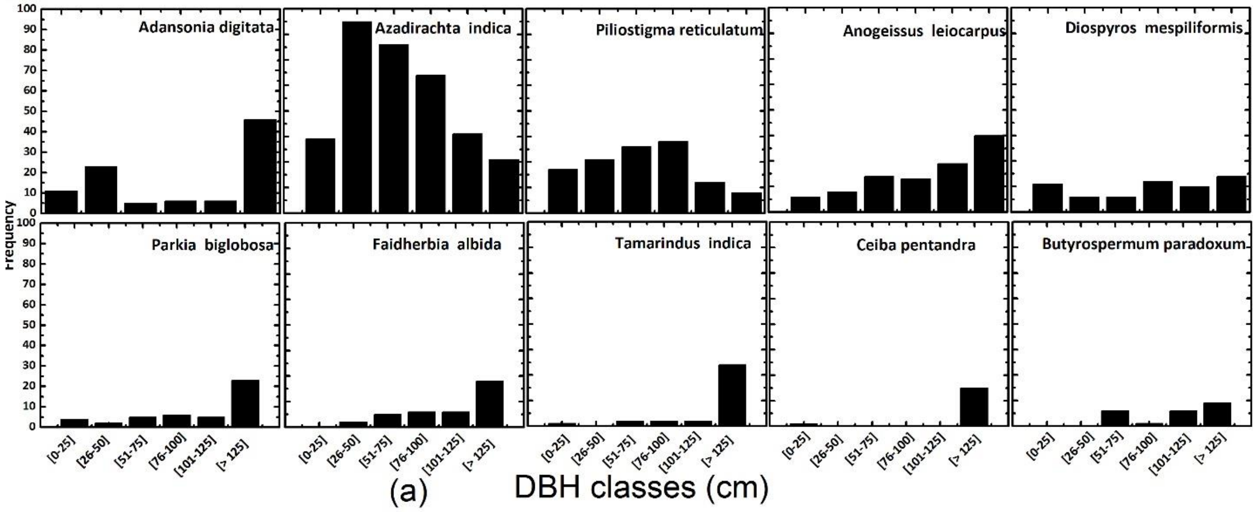
Table 4 shows the IVI for the ten most important tree species in each study area. The non-fuelwood baobab tree *Adansonia digitata* appears over-represented due to its swollen trunk, thus large DBH, which is disproportionate to its crown size. It is retained in the tables due to its diverse non-fuel uses (including food, fibre, and medicinal). Besides baobab, the common dominants in all three study areas are the exotic Neem tree, *Azadirachta indica*, and the Sudan zone species *Piliostigma reticulatum* (Appendix A), both of which are highly valued for fuelwood use. Both species show active regeneration in all three study areas, with many trees in the lower DBH classes (Figure 5), and all size classes strongly represented. Table 5 also suggests that these two species have become dominant recently, as they were absent from the dominant species recorded in Study area 1 in 1981, and in Study area 3 *P. reticulatum* is now the most common tree with an Importance Value (IVI) of 67, compared with 23 in 1981.

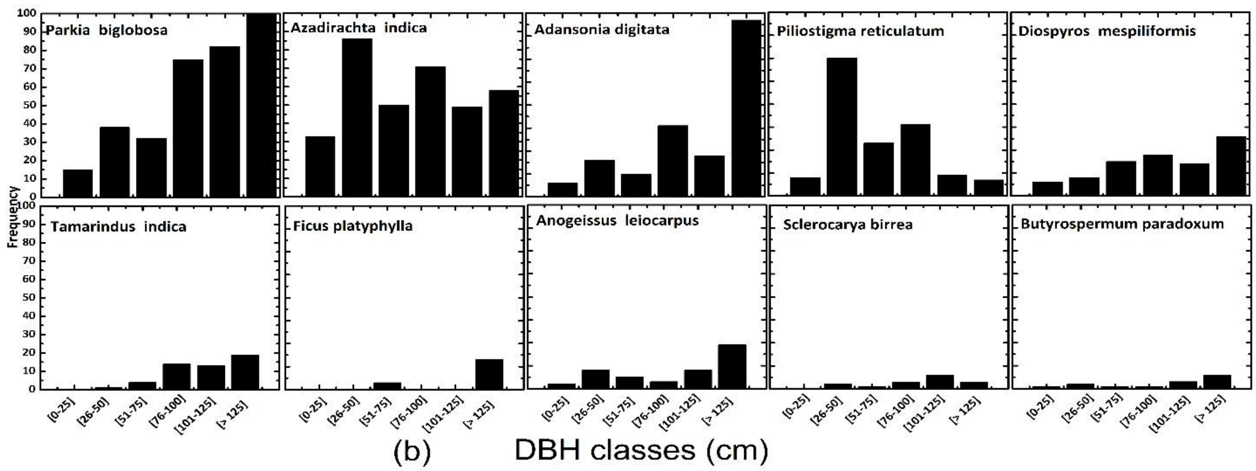
The DBH spectra (Figure 5) show that only four of the dominant ten species in Study area 1, and three of the dominant ten species in Study are 2 are actively regenerating and all these are preferred fuelwood species Neem (*Azadirachta indica* A.Juss), Kargo (*Piliostigma reticulatum*), the African Ebony (*Diospyros mespiliformis*) and the Chewstick Tree (*Anogeissus leiocarpus*). *D. mespiliformis* has high importance and appears to be actively regenerating in all three study areas. With an IVI of 19.3 in 1981 and 17.3 in 2015-16, this preferred fuelwood species has retained its importance among tree products in the local economy. On the other hand the dominant tree in Study area 2, the African Locust Bean (*Parkia biglobosa*) used traditionally for food and fibre, comprises mainly old trees with no evident regeneration, similar to Study areas 1 and 3 where its DBH spectrum is dominated by the largest class. Similarly, the dominant species recorded in Study area 1 in 1981, *Faidherbia albida*, which is traditionally valued for its retention of leaves in the dry season, providing fodder and shade, is now only 7th in importance, with its DBH spectrum dominated by large old trees and no evident regeneration. The non-fuelwood tree *A. digitata*, although occupying 1st, 3rd and 2nd places in importance in study areas 1, 2 and 3 respectively, is heavily weighted to the largest DBH class suggesting its declining importance in recent decades. Discussions with local farmers indicated a decline in species diversity, with loss of many traditionally protected species and shift toward species which are fast-growing and are preferred fuelwood species Neem and *P*. *reticulatum*.

**Table 4.** Tree species dominance in farmed parkland.

| No. | Study Area 1 | IVI | Study Area 2 | IVI | Study Area 3 | IVI |
|---|---|---|---|---|---|---|
| 1 | Adansonia digitata | 49.5 | Parkia biglobosa | 70.3 | Piliostigma reticulatum * | 66.5 |
| 2 | Azadirachta indica* | 44.8 | Azadirachta indica * | 39.8 | Adansonia digitata | 47.4 |
| 3 | Piliostigma reticulatum * | 24.4 | Adansonia digitata | 34.0 | Azadirachta indica* | 37.5 |
| 4 | Anogeissus leiocarpus * | 20.9 | Piliostigma reticulatum * | 16.7 | Hyphaene thebaica | 25.1 |
| 5 | Diospyros mespiliformis* | 17.3 | Diospyros mespiliformis* | 16.0 | Diospyros mespiliformis* | 20.4 |
| 6 | Parkia biglobosa | 16.1 | Tamarindus indica* | 14.5 | Lannea acida | 18.9 |
| 7 | Faidherbia albida | 15.6 | Ficus platyphylla | 13.1 | Parkia biglobosa | 13.0 |
| 8 | Tamarindus indica* | 15.3 | Anogeissus leiocarpus * | 13.1 | Borassus aethiopum | 7.5 |
| 9 | Ceiba pentandra | 10.9 | Sclerocarya birrea | 6.5 | Anogeissus leiocarpus * | 7.0 |
| 10 | Butyrospermum paradoxum | 5.8 | Butyrospermum paradoxum | 4.6 | Acacia nilotica | 5.9 |

* Species preferred for fuelwood use


Adansonia digitata
Azadirachta indica
Piliostigma reticulatum
Anogeissus leiocarpus
Diospyros mespiliformis
Parkia biglobosa
Faidherbia albida
Tamarindus indica
Ceiba pentandra
Butyrospermum paradoxum
Frequency
[0-25]
[26-50]
[51-75]
[76-100]
[101-125]
[> 125]
(a)
DBH classes (cm)


Parkia biglobosa
Azadirachta indica
Adansonia digitata
Piliostigma reticulatum
Diospyros mespiliformis
Tamarindus indica
Ficus platyphylla
Anogeissus leiocarpus
Sclerocarya birrea
Butyrospermum paradoxum
Frequency
[0-25]
[26-50]
[51-75]
[76-100]
[101-125]
[> 125]
(b)
DBH classes (cm)

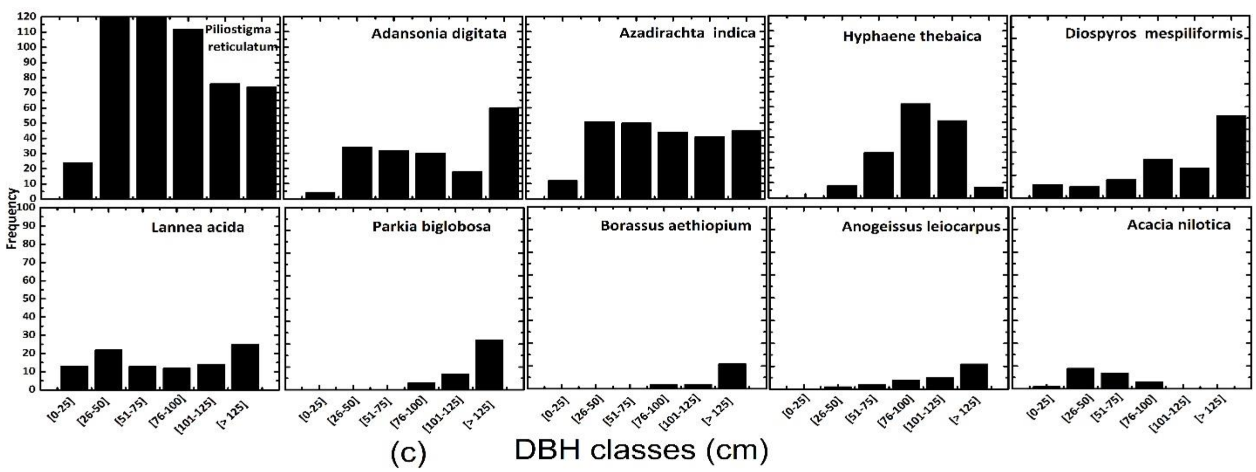

Piliostigma reticulatum
Adansonia digitata
Azadirachta indica
Hyphaene thebaica
Diospyros mespiliformis
Lannea acida
Parkia biglobosa
Borassus aethiopium
Anogeissus leiocarpus
Acacia nilotica
Frequency
[0-25]
[26-50]
[51-75]
[76-100]
[101-125]
[> 125]
(c)
DBH classes (cm)

**Figure 5.** DBH spectra for ten dominant species in Study area 1 (a), Study area 2 (b) and Study area 3 (c).

**Table 5.** Species trends (1981-2016) for Study areas 1 and 3. No data are available for Study area 2 in 1981.

| | STUDY AREA 1 | | | | STUDY AREA 3 | | | |
|---|---|---|---|---|---|---|---|---|
| No. | 1981 | IVI | 2015-2016 | IVI | 1981 | IVI | 2015-16 | IVI |
| 1 | Faidherbia albida | 38 | Adansonia digitata | 50 | Adansonia digitata | 121 | Piliostigma reticulatum* | 67 |
| 2 | Adansonia digitata | 37 | Azadirachta indica* | 45 | Faidherbia albida | 32 | Adanasonia digitata | 47 |
| 3 | Parkia biglobosa | 29 | Piliostigma reticulatum* | 24 | Piliostigma reticulatum* | 23 | Azadirachta indica* | 38 |
| 4 | Diospyros mespiliformis* | 19 | Anogeissus leiocarpus* | 21 | Balanites aegyptiaca | 21 | Hyphaenae thebaica | 25 |
| 5 | Anogeissus leiocarpus* | 17 | Diospyros mespiliformis* | 17 | Combretum fragrans | 16 | Diospyros mespiliformis* | 20 |
| 6 | Tamarindus indica* | 15.1 | Parkia biglobosa | 16 | Sclerocarya birrea | 15 | Lannea acida | 19 |

* Species preferred for fuelwood use

### 3.4 Farm questionnaires on tree densities and species

Responses to questions about tree densities (Table 6) initially indicated that farmers perceived trees to be declining, as 90% indicated decline. However, typical replies to question 3 about changes in the total numbers of trees, was mainly answered not in terms of tree numbers, but by mentioning which species had declined or disappeared. Moreover, farmers stated the need for faster growing species in response both to question 3 about tree numbers as well as to question 2 about species. This led us to suspect that the discrepancy between our data and farmers' perceptions may, at least in part, arise from inability to distinguish between the concepts of tree numbers and tree species due to a sense of alarm at the disappearance of many valuable indigenous species such as *Parkia biglobosa, Ceiba pentandra* , and *Adansonia digitata*, given the role of trees of different species in the Hausa cultural and religious heritage (Cline-Cole, 1998; Etkin, 2002; Tomomatsu, 2014).

**Table 6**. Farm questions and responses about tree numbers and tree species

| Question | Summary of Responses |
|---|---|
| 1.Have you noticed any changes in the **species** of trees over the last 20, 30, 40 or 50 years? –which species are fewer now, and which species are more common now? | Yes, fewer species now; loss of traditional species: P. biglobosa, A. digitata, B. paradoxum, F. albida, B. aegyptiaca, S. birrea, V. doniana, Z. spina-christi: appearing are A. indica, P. thonningii |
| 2.What are the reasons for the change in **species** of trees? | Population growth and need more space for crops: need faster growing trees: traditional species need more moisture |

| | |
|---|---|
| 3.Have you noticed any changes in the **total number** of trees on your farm over the last 20, 30, 40 or 50 years – are there more total trees now or fewer trees now? | Yes, before there were many trees, now fewer trees/species |
| 4.What are the reasons for the change in **total numbers** of trees | Population growth, trees cut for fuel, fuelwood use, drought, wind, don't want thorny trees, trees used for income, need fast growing trees because of population growth |
| **4.** If you plant or grow any new trees what species would you chose? | A. indica (84%), M.oleifera (53%), M. indica (43%), C.glutinosum (28%), P. biglobosa (28%) |
| **5.** Why would you chose this species? | Fuelwood (100%), Food (62%), Medicine (18%) |
| **6.** What things can you buy in the market now that you used to get from trees? | Medicine, Vitamin C, sweets, cotton stuffing, skin products, soup, food |
| **7.** Which one is best, tree products or market products? | Prefer tree (50%), Prefer market (7%), Prefer market because tree processors/tree products not available (25%) |

NB. Merged questionnaires from Kano West and Daura. (%) refers to percentage of farmers with such response. All farmers over 40 years old. Example of a typical reply to Q3 "Thirty years before there were 22 species of trees. Now there are fewer species, of only 8 in number.

## 4. Discussion

Previous reports of greening in the Sahel based on NDVI, as well as increasing tree numbers since the 1970s to 80s drought period, conclude that biomass trends, whether woody or herbaceous, follow trends in rainfall. For example Brandt et al. (2014a) observe that tree densities have recovered somewhat since the drought period but are still below those of the 1960s pre-drought period, while Hänke et al. (2016) and Brandt et al. (2017) observe recovery, but only back to 1960s levels by 2006 and 2015 respectively. Therefore, the marked increase in tree numbers in the Kano region over the last 5 decades observed here is surprising when set in the context of recent work in West Africa.

While it is true that rainfall in Kano region generally has recovered since the 1980s, back to 1960s levels, tree densities in the farmed parkland hinterlands of Kano city, are at least double those of the 1960s. A steady increase is observed, even through the drought decades, when all other reports indicate severe decline in tree numbers and in woody vegetation. Accompanying this increase in tree density has been an even greater increase in potential fuelwood production which has increased by approximately 300% in study area 1 and 600% in Study area 3, since 1981. Decline in the non-fuelwood species *Adansonia digitata* as well as in other indigenous and slower-growing species traditionally valued as much for uses other than fuel , indicated by their non-regeneration in all three study areas (Figure 5), points to the demand for wood fuel as a likely explanation of the observed trends. The fact that most trees have multiple uses including fuelwood (Cline-Cole, 1998) makes it difficult to identify fuelwood demand as the main driver of the observed increased tree densities. However, several factors lead us to believe this as the most likely explanation. Firstly, farm questionnaires indicated a preference for fast-growing species, with many farmers stating their preference for Neem because it can be lopped aggressively and recovers within one or two years. Secondly, as the response to questions 6 and 7 indicates, tree products such as food, fibre, medicinal and cosmetics, are now readily available as cheap manufactured imports. Furthermore, such uses do not preclude the woody component being lopped or eventually felled for fuel. Thirdly, whereas all similar recent studies have been conducted in the less densely populated countries of the Sahel zone, government energy policies in Nigeria largely determine fuel options (Maconachie et al, 2009; Cline-Cole and Maconachie, 2016). Given that electricity is rare in rural areas, and kerosene prices unpredictable, a rural population of 7 million in Kano region relies on wood for cooking and heating, and the urban population now estimated at over 3.8 million (Geonames, 2017) relies on wood due to its affordability and availability. The recent massive growth of population in Kano city and region (ie. doubling in the 15 years up to the last population census in 2006) would not have been possible without a parallel increase in the main energy source, wood fuel. Land fragmentation due to traditional inheritance customs, would require more farmland trees to supply additional households, as farmers indicated they rarely buy wood. The six-fold increase in fuelwood volume observed in the outer hinterlands compared to three-fold increase nearer the city since 1981, illustrates the growing demand, as nearby sources would be exploited before more distant ones. The observed increased importance of preferred fuelwood species *A. indica* and *P. reticulatum*, among farmland trees has resulted in decline of other species traditionally valued as much, or more for their food, fibre, fodder and medicinal uses. Cheap alternatives to products traditionally derived from trees, such as stock cubes, beverages, painkillers, petroleum jelly, foam stuffing and plastics are now available in the consumer economy, and affordable from the sustained income farmers gain from selling wood. The observed increase in tree densities in the face of massive population growth, is in fact in line with work in Kano region over three decades ago (Cline-Cole et al., 1990), suggesting that in the face of Malthusian-type pressure on available supplies, a somewhat Boserupian response appears to be emerging.

The on-going, apparent reduction in species diversity observed in this study, also noted by studies in the Sahel zone (Brandt et al., 2014a; Gonzalez et al., 2012; Hänke et al., 2016), has largely been attributed to a climate-induced shift towards more drought-tolerant species. Observations of higher recovery from the 1970s to 80s drought nearer to houses (Hänke et al., 2016) and to villages (Brandt et al., 2014a) recognize that human factors play a role in areas where population growth has led to agricultural intensification. However, the recent concentration on species valued for fuel concurrent with rapid population growth observed in this study, strongly suggests the dominant role of socio-economic factors, possibly with climate playing a minor role.

It is also surprising that our tree surveys from fieldwork and time series of images, conflict with farmers' perceptions of tree stocks, both from our own study and those of previous researchers (Maconachie et al., 2009; Maconachie and Binns, 2006). Farmers apparently perceive tree stocks on farmland to be declining accompanied by a loss of traditional parkland species such as *P. biglobosa*, *F. albida* and *A. digitata*. However, as farmers rarely buy wood, and the rural population has doubled between 1991 and 2006, a corresponding increase in farmland tree stocks does seem inevitable. Farmers' responses may be influenced by mixed perceptions comprising insecurity in the face of current and impending climate change and increasing aridity, as well as alarm at the disappearance of valuable indigenous trees such as *P. biglobosa*, *C. pentandra*, *A. digitate, A. leiocarpus* and *A. albida*, which supply many free products and are part of their heritage (Tomomatsu, 2014). The practice known as **wankan jegu** whereby newly delivered mothers bathe twice daily for 40 days in scalding hot water, requiring an enormous amount of fuelwood

(Maconachie and Binns, 2006), may also influence respondents' perceptions about fuelwood availability, as births in Kano region more than doubled between 1991 and 2006. Perceptions that interviewers have influence, and are thus able to alleviate long-standing frustrations at the fluctuating price of kerosene and lack of electric power supply, may also prompt farmers to indicate that trees are disappearing. Cline-Cole's observation that field foresters in Kano region were reluctant to admit that claims of healthy tree stocks were unlikely to attract assistance from donor and funding agencies (Cline-Cole, 1998) confirms the need to interpret farmer responses in broad context.

## 5. Conclusion

The findings of this study conflict with other similar work carried out in West Africa, which has mainly attributed changes in greenness and woody vegetation, to climatic fluctuations such as decadal droughts and recent global warming. Gonzalez et al. (2012) attribute their observed declining tree densities and species richness across the West African Sahel, to climatic, rather than human factors. They especially invoke global climate change, consistent with other reports of drought-induced tree dieback from around the world (Allen et al., 2010). That tree stocks in farmland have appeared to keep pace with massive population growth, even contradicting local perceptions of degradation, is surprising, but confirms earlier observations of the resilience of trees as both an economic and social component of the agricultural production system.

The reduction in species diversity noted in this study, and by others (Brandt et al., 2014a; Gonzalez et al., 2012; Hänke et al., 2016) may not be so alarming given the available supply from other sources, of traditional tree products, although market fluctuations may dictate future prices. Of greater concern is the continued overwhelming dependence on biomass for fuel by a still rapidly growing population across northern Nigeria. Return to the drought conditions of previous decades coupled with tree death due to climate change may have serious consequences for rural households for whom the longevity of woody vegetation offers security against rainfall variability and crop failure. Urbanites' reliance on wood may be less affected, as the fuelwood hinterland of Kano has expanded with modern transport, to the more wooded Guinea zone, and has potential to expand and contract according to demand.

The Sudan zone comprises 40% of Nigeria's land area, and it is likely (given the range of geographical environments covered in the three distinct study areas) that the trends in tree stocks observed here are applicable to other parts of Nigeria's Sudan zone. However, whether they are applicable to other parts of savanna Africa is probably dependent on national government energy policies, as Nigeria's continued dependence on biomass fuel is clearly both unfortunate and unusual.

## Acknowledgments

This work is done through a PhD fellowship grant from the Research Grants Council of Hong Kong, grant No. RTYU. Authors would also like to acknowledge the help from Department of Geography, Bayero University, Kano, Nigeria, for providing an archive of aerial photographs and arrangements for field survey. Dr Asma Ibrahim of the National Centre for Remote Sensing, Abjua, and Dr Luka Buba and Dr Salisu Mohammed, Muhammad Zikirullah Aliyu and Isa Sani of Bayero University, provided valuable assistance during field data collection.

## References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Anyamba, A., Tucker, C.J., 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981-2003. J. Arid Environ. 63, 596–614. https://doi.org/10.1016/j.foreco.2009.09.001

Audu, E., 2013. Fuel wood consumption and desertification in Nigeria. Int. J. Sci. Technol. 3, 1–5.

Boffa, J.M., 1999. Agroforestry Parkland in Sub-Saharan Africa: FAO Conservation Guide 34. FAO, Rome.

Brandt, M., Romankiewicz, C., Spiekermann, R., Samimi, C., 2014a. Environmental change in time series - An interdisciplinary study in the Sahel of Mali and Senegal. J. Arid Environ. 105, 52–63. https://doi.org/10.1016/j.jaridenv.2014.02.019

Brandt, M., Tappan, G., Diouf, A., Beye, G., Mbow, C., Fensholt, R., 2017. Woody vegetation die off and regeneration in response to rainfall variability in the West African Sahel. Remote Sens. 9, 39. https://doi.org/10.3390/rs9010039

Brandt, M., Verger, A., Diouf, A.A., Baret, F., Samimi, C., 2014b. Local vegetation trends in the sahel of mali and senegal using long time series FAPAR satellite products and field measurement (1982-2010). Remote Sens. 6, 2408–2434. https://doi.org/10.3390/rs6032408

Capecchi, V., Crisci, A., Lorenzo, G., Maselli, F., Vignaroli, P., 2008. Analysis of NDVI trends and their climatic origin in the Sahel 1986–2000. Geocarto Int. 23, 297–310. https://doi.org/10.1080/10106040801950492

Cline-Cole, R., 1998. Knowledge claims and landscapes: alternative views of thefuelwood-degradation nexus in northern Nigeria. Environ. Plan. D Soc. Sp. 16, 311–346. https://doi.org/10.1068/d160311

Cline-Cole, R.A., Main, H.A.C., Nichol, J.E., 1990. On fuelwood consumption, population dynamics and deforestation in Africa. World Dev. 18 (4), 513–527. https://doi.org/10.1016/0305-750X(90)90068-9

Cline-Cole, R., Maconachie, R., 2016. Wood energy interventions and development in Kano, Nigeria: A longitudinal, “situated” perspective. Land Use Policy 52, 163–173. https://doi.org/10.1016/j.landusepol.2015.11.014

Condit, R., Sukumar, R., Hubbell, S., Foster, R.B., 1998. Predicting population trends from size distributions : a direct test in a tropical tree community. Am. Nat. 152 (4), 495–509. https://doi.org/10.1086/286186

Etkin, N.L., 2002. Local knowledge of biotic diversity and its conservation in rural Hausaland, northern Nigeria. Econ. Bot. 56 (1), 73–88. https://doi.org/10.1663/0013-0001(2002)056[0073:lkobda]2.0.co;2

Geonames., 2017. http://www.geonames.org/2335204/kano.htm. Accessed May, 2017

Gonzalez, P., Tucker, C.J., Sy, H., 2012. Tree density and species decline in the African Sahel attributable to climate. J. Arid Environ. 78, 55–64. https://doi.org/10.1016/j.jaridenv.2011.11.001

Hänke, H., Börjeson, L., Hylander, K., Enfors Kautsky, E., 2016. Drought tolerant species dominate as rainfall and tree cover returns in the West African Sahel. Land Use Policy 59, 111–120. https://doi.org/10.1016/j.landusepol.2016.08.023

Hazewinkel, M., 2001, Affine transformation, Encyclopedia of Mathematics, Springer,

Herrmann, S.M., Tappan, G.G., 2013. Vegetation impoverishment despite greening: A case study from central Senegal. J. Arid Environ. 90, 55–66. https://doi.org/10.1016/j.jaridenv.2012.10.020

Hiernaux, P., Diarra, L., Trichon, V., Mougin, E., Soumaguel, N., Baup, F., 2009. Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). J. Hydrol. 375, 103–113. https://doi.org/10.1016/j.jhydrol.2009.01.043

IPCC, 2014. Climate Change 2014 Impacts, Adaptation, and Vulnerability Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. https://doi.org/ 10.1007/s13398-014-0173-7.2

Karlson, M., Reese, H., Ostwald, M., 2014. Tree crown mapping in managed woodlands (Parklands) of semi-arid West Africa using WorldView-2 imagery and geographic object based image analysis. Sensors (Switzerland) 14, 22643–22669. https://doi.org/10.3390/s141222643

Karlson, M., Ostwald, M., 2016. Remote sensing of vegetation in the Sudano-Sahelian zone: A literature review from 1975 to 2014. J. Arid Environ. 124, 257–269. https://doi.org/10.1016/j.jaridenv.2015.08.022

Kershaw, K.A.,1974. Quantitative and dynamic plant ecology, Elsevier, 308pp.

Knauer, K., Gessner, U., Dech, S., Kuenzer, C., 2014. Remote sensing of vegetation dynamics in West Africa. Int. J. Remote Sens. 35, 6357–6396. https://doi.org/10.1080/01431161.2014.954062

Lykke, A.M., 1998. Assessment of species composition change in savanna vegetation by means of woody plants' size class distributions and local information. Biodivers. Conserv. 7, 1261–1275. https://doi.org/10.1023/A:1008877819286

Maconachie, R.A., Binns, T., 2006. Sustainability Under Threat ? The dynamics of Environmental Change and Food Production in Peri-Urban Kano, Northern Nigeria. Land Degrad. Dev. 17 (2), 159–171. https://doi.org/10.1002/ldr.722

Maconachie, R., Tanko, A., Zakariya, M., 2009. Descending the energy ladder? Oil price shocks and domestic fuel choices in Kano, Nigeria. Land Use Policy 26 (4), 1090–1099. https://doi.org/10.1016/j.landusepol.2009.01.008

Machonachie, R., 2013. Urban pressure and tree cover. Chapter 26 in A.I. Tanko and S.B. Momale (eds) Geography of the Kano Region, Adonis and Abbey publishers, UK., 551pp.

McDonald, R.A., 1995. CORONA: success for space reconnaissance, a look into the Cold War, and a revolution for intelligence. Photogramm. Eng. Remote Sens. 61, 689–720.

Mishra, N.B., Crews, K.A., Neeti, N., Meyer, T., Young, K.R., 2015. MODIS derived vegetation greenness trends in African Savanna: Deconstructing and localizing the role of changing moisture availability, fire regime and anthropogenic impact. Remote Sens. Environ. 169, 192–204. https://doi.org/10.1016/j.rse.2015.08.008

Mortimore, M., 2000. Profile of rainfall change and variability in the Kano-Maradi region, 1960–2000, Drylands Research Working Paper 25, Drylands Research, Crewkerne, Somerset.

Mortimore, M., Wilson, J., 1965. Land and people in the Kano close-settled zone; a survey of some aspects of rural economy in the Ungogo District, Kano Province: A report to the Greater Kano Planning Authority.

Naibbi, A.I., Healey, R.G., 2013. Northern Nigeria's Dependence on Fuelwood: Insights from Nationwide Cooking Fuel Distribution Data. Int. J. Humanit. Soc. Sci. 3, 160–173.

National Bureau of Statistics, 2011. Annual Abstract of Statistics. Published by the Federal Republic of Nigeria, Table 111.

National Population Commission, 2006. Federal Republic of Nigeria 2006 Population and Housing Census, Priority Tables Vol. VII, Abuja, Nigeria.

Nichol, J.E., 1989. Ecology of fuelwood production in Kano, Northern Nigeria. J. Arid Environ. 16, 347–360.

Olsson, L., Eklundh, L., Ardö, J., 2005. A recent greening of the Sahel - Trends, patterns and potential causes. J. Arid Environ. 63, 556–566. https://doi.org/10.1016/j.jaridenv.2005.03.008

Padwick, C., Scientist, P., Deskevich, M., Pacifici, F., Smallwood, S., 2010. WorldView-2 pan-sharpening, in: ASPRS 2010. pp. 26–30.

Tappan, G.G., Sall, M., Wood, E.C., Cushing, M., 2004. Ecoregions and land cover trends in Senegal. J. Arid Environ. 59, 427–462. https://doi.org/10.1016/j.jaridenv.2004.03.018

Thornton, P., Jones, P., Owiyo, T., Kruska, R., Herrero, M., Kristjanson, P., Notenbaert, a, Bekele, N., Omolo, a, 2006. Mapping climate vulnerability and poverty in Africa. Rep. to Dep. Int. Dev. ILRI PO Box 30709, 171. https://doi.org/http://www.dfid.gov.uk/research/climate-change.asp.

Tiffen, M., 2001. Profile of demographic change in the Kano-Maradi region, 1960–2000, Drylands Research Working Paper 24.

Timberlake, J., Chidumayo, E., Sawadogo, L., 2010. Distribution and Characteristics of African Dry Forests and Woodlands, The dry forests and woodlands of Africa: managing for products and services. doi:10.4324/9781849776547

Tomomatsu, Y., 2014. Parkia biglobosa-dominated cultural landscape: an ethnohistory of the Dagomba political institution in farmed parkland of northern Ghana. J. Ethnobiol. 34(2), 153-174. https://doi.org/10.2993/0278-0771-34.2.153

UNEP, 2007. Freshwater Resources, Sudan Post-Conflict Environmental Assessment.

UNICEF, 2014. Generation 2030|Africa, IGARSS 2014. doi:10.1007/s13398-014-0173-7.2

Vincke, C., Diédhiou, I., Grouzis, M., 2010. Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). J. Arid Environ. 74, 268–276. https://doi.org/10.1016/j.jaridenv.2009.08.006

**Appendix A**. Field inventoried tree species, families, abundance and their ecological zone.

| Tree species | Family | Ecological Zone | Study Area 1 (37 ha) | Study Area 2 (137 ha) | Study Area 3 (60 ha) |
|---|---|---|---|---|---|
| Acacia albida | Mimosaceae | Sudan | 38 | 10 | 8 |
| Acacia nilotica | Mimosaceae | Sahel | 14 | 7 | 17 |
| Acacia seyal | Mimosaceae | Sahel | 6 | 0 | 0 |
| Acacia sieberiana | Mimosaceae | Guinea | 8 | 0 | 6 |
| Acacia senegal | Mimosaceae | Sahel | 0 | 0 | 3 |
| Adansonia digitata | Bombacaceae | Sudan | 94 | 157 | 166 |
| Albizia chivalieri | Mimosacea | Sahel | 3 | 0 | 15 |
| Anacardium occidentali | Anacardiaceae | Sudan | 0 | 0 | 3 |
| Anogeissus leiocarpus | Combretacea | Guinea | 84 | 51 | 21 |
| Anona senegalensis | Annonaceae | Guinea | 0 | 1 | 0 |
| Azadirachta indica | Meliacea | Exotic | 236 | 338 | 212 |
| Balanites aegyptiaca | Balanitaceae | Sahel | 5 | 3 | 5 |
| Bauhinia rufescens | Caesalpiniaceae | Sudan | 0 | 1 | 0 |
| Bombax costatum | Bombacaceae | Guinea | 1 | 0 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Borassus aethiopum | Arecaceae | Sudan | 4 | 5 | 16 |
| Boswellia dalzielli | Burseraceae | Sudan | 0 | 24 | 0 |
| Calotropis procera | Asclepiadaceae | Guinea | 3 | 1 | 1 |
| Carica papaya | Caricaceae | Guinea | 0 | 2 | 4 |
| Cassia sieberiana | Caesalpiniaceae | Guinea | 0 | 0 | 34 |
| Cassia singueana | Leguminosae | Guinea | 1 | 0 | 0 |
| Ceiba pentandra | Malvaceae | Guinea | 16 | 11 | 0 |
| Combretum glutinosum | Combretaceae | Sudan | 1 | 11 | 0 |
| Combretum micranthum | Combretaceae | Sudan | 3 | 2 | 4 |
| Commiphora africana | Burseraceae | Sahel | 8 | 17 | 0 |
| Detarium microptera | Caesalpiniaceae | Guinea | 2 | 1 | 3 |
| Dichrostachys cinerea | Mimosaceae | Sudan | 4 | 0 | 0 |
| Diospyros mespiliformis | Ebenaceae | Guinea | 60 | 93 | 65 |
| Entada africana | Mimosaceae | Guinea | 7 | 4 | |
| Euphorbia kamerunica | Euphorbiaceae | Sahel | 0 | 0 | 1 |
| Ficus sycomorus | Moraceae | Sudan | 6 | 1 | 7 |
| Ficus glumosa | Moraceae | Sudan | 0 | 3 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Ficus iteophylla | Moraceae | Sudan | 3 | 4 | 1 |
| Ficus platyphylla | Moraceae | Guinea | 1 | 16 | 1 |
| Ficus polita | Moraceae | Guinea | 0 | 1 | 0 |
| Ficus populifolia | Moraceae | Sudan | 2 | 0 | 0 |
| Ficus thonningii | Moraceae | Guinea | 15 | 3 | 0 |
| Gardenia erubescens | Rubiaceae | Guinea | 1 | 2 | 0 |
| Hyphaene thebaica | Arecaceae | Sahel | 10 | 9 | 118 |
| Ipomoea argentaurata | Convolvulaceae | Sudan | 1 | 0 | 0 |
| Jatropha curcas | Euphorbiaceae | Sudan | 1 | 0 | 0 |
| Khaya senegalensis | Meliaceae | Guinea | 0 | 0 | 15 |
| Lannea acida | Anacardiaceae | Guinea | 2 | 19 | 75 |
| Mangifera indica | Anacardiaceae | Sudan | 17 | 37 | 7 |
| Moringa oleifera | Moringaceae | Sudan | 0 | 1 | 7 |
| Parkia biglobosa | Mimosaceae | Guinea | 43 | 435 | 31 |
| Phoenix dactilifera | Arecaceae | Sahel | 1 | 2 | 0 |
| Piliostigma reticulatum | Caesalpiniaceae | Sudan | 116 | 114 | 431 |
| Sclerocarya birrea | Anacardiaceae | Sudan | 18 | 20 | 10 |
| Steriospermum kunthianum | Bignoniaceae | Guinea | 0 | 1 | 0 |
| Strychnos spinosa | Loganiaceae | Guinea | 0 | 4 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Tamarindus indica | Caesalpiniaceae | Sudan | 32 | 50 | 7 |
| Terminalia macroptera | Combretaceae | Guinea | 2 | 5 | 0 |
| Viteralleria paradoxa | Sapotaceae | Sudan | 19 | 16 | 1 |
| Vitex doniana | Verbenaceae | Guinea | 8 | 11 | 1 |
| Ziziphus spina-cristi | Rhamnaceae | Sudan | 3 | 9 | 1 |
| Zizyphus mauritiana | Rhamnaceae | Sahel | 1 | 0 | 0 |